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Sectoral patterns versus firm-level heterogeneity - the dynamics of eco-innovation strategies in the automotive sector

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ABSTRACT: This paper sheds light on some important but underestimated elements of green industrial dynamics: the evolution of firms' eco-innovation strategies and activities within a sector. While eco-innovation sectoral case studies have taken place before, our analysis is distinct in investigating the rate, direction and extent of eco-innovation in the automotive sector, represented here by the main automakers, in order to identify possibly sectoral-specific patterns in firms' strategies, as opposed to divergent strategic behaviors, grounded on evolutionary economic theory. We conduct a two-step empirical analysis using patent data from 1965 to 2012. Our findings suggest a process of co-evolution of firms' strategies and indicate that strong sectoral-specific patterns of eco-innovation are present in this sector from the mid-2000s onwards. For fuel cells technologies, however, we observe the formation of two antagonist patterns. A further econometric analysis is conducted and indicates that the positioning of the firms between these two groups is correlated with the firms' profit margins and the size of firms' patent portfolios.

KEYWORDS: eco-innovation; green economy; sectoral patterns; automotive sector; evolutionary dynamics; technological strategies; fuel cell

1. Introduction

The remarkable rise of the green economy as a new techno-economic paradigm (Freeman, 1996) and the role of eco-innovations as mechanisms to reach higher levels of both economic and environmental development have been object of little attention by evolutionary innovation scholars. Furthermore, the focus of the relatively few studies in this field has been mainly on the role of policy mechanisms in influencing eco-innovation e.g. (Hojnik & Ruzzier, 2015; Kemp & Oltra, 2011), rather than the understanding of the green industrial dynamics itself (Andersen and Faria, 2015).

This paper seeks to contribute to the latter combining some of the core assumptions of firm theory at micro-level with meso-level evolutionary frameworks (Nelson, 1991). The basic idea is that firm's technological strategies at micro-level accumulate and ultimately shape the technological development at the sector level. Evolutionary researchers have argued that firms in the same sector could be subject to some convergence in their innovation strategies, forming sector-specific technological trajectories (e.g. Pavitt, 1984; Breschi & Malerba, 1996; Klevorick et al., 1995; Malerba, 2002). While this is a recognized argument in evolutionary research, it is also been contested as evolutionary theories also highlight firm heterogeneity and hence the key importance of firms' technological strategies (Patel & Pavitt, 1997; Peneder, 2010).

As a first step towards understanding this complex theme, this paper aims to undertake a case study of the automotive sector. We aim to analyze the rate, direction and extent of the greening of the automotive sector, highlighting the firm-level dynamics and the green technological strategizing, over the last decades. Using patent data, the paper analyses eco-innovation activities in the automotive sector from 1967 to 2012, i.e. the main period of industrial greening. The eco-innovations considered are restricted to the core automotive innovation, the powertrain. This is partly to delimit the quite comprehensive analysis, partly to allow for a focus on comparing the greening of the mature dominant design, the combustion engine versus the upcoming competing green trajectories (related to respectively hybrid/electric and fuel cell based cars).

In mature markets, firms with better dotation of internal resources or specific combinations of external developing new technologies compared to firms that face inadequate conditions (Abernathy & Clark, 1985). On the other hand, firms' strategies are also influenced by, for instance, country and technology specific elements (Malerba & Orsenigo, 1996). The greening of the automotive sector is characterized by the existence of competing technologies at different development stages and with distinct degrees of differentiation from the dominant design, and therefore the decision to invest in one or more of these technologies might at any given time be more or less influenced by firms' internal versus external characteristics (Wesseling et al., 2015).

Some studies analyze changes in green technological strategies of individual firms in the automotive industry. While some highlight the increase in technological variety due to the greening of the sector (e.g. Frenken et al., 2004; Oltra & Saint Jean, 2009b), others defend that some firms are developing specific green technologies (Pohl & Yarime, 2012; Sierzchula et al., 2012). Many cite successive shifts in firms' strategies between fuel cells, battery electric and hybrid electric technologies during the past 20 years (Konrad et al., 2012; van den Hoed, 2007). Overall, the evidence on the dynamics of eco-innovation in the sector and the factors affecting firms' decision vary somewhat. None of these studies, however, address the research question we ask here: How homogenous is the greening process over time in this sector?

In a previous related paper we focused more on the meso-level dynamics of eco-innovation in the sector (Faria & Andersen, 2015). In this paper, we found a strong reduction in the concentration of green patenting activity within the automotive sector for some core technologies, namely Advanced Internal Combustion Engines (ICE), Hybrid/Electric Engines, and Complex patents[1] in the past decades. However, a fourth group, *fuel cells*, remained relatively more concentrated in few firms. In this paper we seek to expand on these findings, with a particular emphasis on investigating how the aggregate reduction in patenting concentration is reflected in the firm-level data, and why the fuel cell case differ from the others.

To some degree this paper represents a narrow perspective on innovation. The analysis has due to space limitations been restricted to the automotive sector only while excluding suppliers. Nevertheless, we argue that the degree of sectoral greening can be analyzed at the sector level only, presuming that the role of suppliers is likely to be distributed across the sector. The focus of the paper is strictly on patenting activities, which excludes to a high degree an analysis of the institutional setting and its changes over time in the period analyzed. We argue that these delimitations are necessary in order to carry out a comprehensive, detailed analyzed of the eco-innovative activities within the sector, and that in fact they open room for future complementary research that includes other actors and compare different data sources.

Overall, our findings suggest a process of co-evolution of firms' strategies within the sector and indicate that sectoral-specific regularities in the eco-innovation patterns are increasingly present in this sector, adding up

[1] See Section 3 for a description of this group.

to the still incipient literature on the existence of sectoral patterns of eco-innovation (e.g. Andersen & Faria, 2015; Mazzanti & Zoboli, 2006; Oltra & Saint-Jean, 2009a). For fuel cells technologies, however, we observe the formation of two opposite patterns, and our statistical analysis indicates that the positioning of the firms between these two groups was significantly correlated with the firms' profit margins and the size of patent portfolio.

The paper is organized as follows: in Section 2, we conduct a critical literature review on the determinants of changes in firms' technological strategies for innovation and eco-innovation, and discuss the greening of the automotive sector in perspective. Section 3 presents the data preparation and methodological steps for the descriptive and econometric procedures. Section 4 presents the results of both analyses and section 5 concludes.

2. Literature review

2.1 Determinants of changes in firms' technological strategies

As Faber & Frenken (2009) argue, the strength of the evolutionary perspective "(…) lies in its strong microeconomic foundations. It builds on behavioral theory of the firm and provides a more realistic description of the technological black box" (p. 467). Differences in firm behavior and characteristics have a crucial role in explaining innovation dynamics and the study of the innovation dynamics at the macro and meso levels must include an understanding of which factors influence changes in firms' *technological strategies*, as these factors reflect the creation and selection mechanisms (Nelson, 1991).

A technological strategy can be understood as continuous alignments between firms' internal capabilities/competencies and external conditions in unique arrangements in order to generate and sustain competitive advantages (Christensen *et al.*, 1987, Porter, 1996). In this sense, organizations operating in lean environments tend to develop a short-term mentality and avoid technological experimentation (Aldrich, 1979; Rothenberg & Zyglidopoulos, 2003), directing innovative search to the neighborhood of the established technologies in order to exploit existing firm-specific assets and competences and avoid potential risks, often generating core-rigidities[2] (Dosi, 1988), unless sufficient opportunities arise and outshine such inertial forces, so that firms change their strategies towards new trajectories (Perez, 2009).

In lean and mature markets, firms with better dotation of internal resources[3] and/or healthier financial records – and therefore greater flexibility – may perceive smaller risks of developing new technologies compared to struggling firms that face scarce or inadequate internal resources to bet and bigger obstacles to obtain external funding for their R&D activities (Barney, 1991; Cainelli et al., 2006; Patel & Pavitt, 1997). Moreover, external elements – including the characteristics of regulatory, competitive and scientific/technological environments, can generate both incentives or obstacles to change (Perez, 2009; Porter & Van der Linde, 1995). General economic conditions, reputation scandals and crises may also exert

[2] Numerous studies point out that this inertia may promote the entrance of new firms that perceive smaller risks due to their absence of organizational and technological inertial forces (Abernathy & Utterback, 1978; Anderson & Tushman, 1990).

[3] By *internal resources* we mean all resources firms possess to undertake their innovative activities including, for example, their capabilities, R&D structure, organizational routines, tacit knowledge, alliances and networks (Barney, 1991).

important influences in firms' willingness to change technological strategies (Archibugi et al., 2013; Paunov, 2012).

Since firms in the same sector or region often share internal characteristics and are subject to similar external conditions (i.e. regulations, competition), collective perceptions about technologies' risks and opportunities might arise, originating sector- (Klevorick et al., 1995; Malerba, 2002; Pavitt, 1984) or geographic-specific patterns of innovation (Cooke et al., 1997; Lundvall, 1992). On the other hand, distinct patterns may arise in the same sector or country due to firm heterogeneity, i.e. differences in internal resources or bounded rationality (Dosi, 1997; Leiponen & Drejer, 2007; Peneder, 2010).

Observable changes in technological strategies can be considered indicators of perceived opportunities from new technologies. Observing the (in)existence of patterns of change in firms technological strategies improves our understanding of which dimensions stand out, influencing the innovative change (Patel & Pavitt, 1997). Considering the green innovative dynamics, Cainelli et al. (2015) argues that firms' internal and external characteristics play a crucial role to understand eco-innovation's development due to its higher complexity (in terms of novelty, uncertainty and variety) when compared with established technologies.

Among the eco-innovation literature, however, scholars have been mainly focusing on the role of institutional mechanisms such as environmental policy instruments in influencing firms' green technological strategies, given the specific challenges and barriers that the market forces face in the greening process such as the "double externality problem" (Johnstone et al., 2010; Porter & Van der Linde, 1995; Rennings, 2000; van den Hoed, 2007). Despite the substantial contribution to the understanding of aggregated, general eco-innovation determinants, this literature barely touches on how firms under similar institutional stimuli form their green technological portfolios.

As Berrone & Fosfuri (2013, p. 892) arguments, "(…) little is known as to why some firms engage in more environmental innovation than others and, perhaps more important, under what conditions firms pursue this type of innovation". There's a lack of understanding on how different dimensions affect a same group of firms to change their technological strategies towards clean technologies and become specialized. Our objective in this paper is to shed some light on this topic by investigating one case, namely the dynamics of eco-innovation in the automotive sector over the last decades.

2.2 The greening of the automotive sector

The automotive sector is a mature, capital intensive industry where strong competitive forces are present, pushing firms to focus on their core competences and inhibiting the emergence of new competitors, as well as alternative business models and technological trajectories (Abernathy & Clark, 1985; Breschi & Malerba, 1996). Accordingly, the technological regime of the sector is characterized by the introduction of incremental innovations based on a *dominant design* composed by some fundamental features such as internal combustion engines (ICE), all-steel car bodies, multi-purpose character, and fully integrated productive processes (Orsato & Wells, 2007).

Not until the 1960s and 1970s did green parameters begin to play a role as the negative environmental impact of automobiles arose as an important issue in the early environmental agenda (Høyer, 2008). Noticeably at that time, it influenced the creation of the first tailpipe emission standards – such as the U.S. Clean Air Act and the European regulation ECE 15/01 – followed by other national and regional environmental regulations targeted towards automobiles and related activities (Faiz et al., 1996). As those early regulations have proved insufficient to solve the environmental issues pointed, a second wave of regulations, incentives and research collaboration projects has started from the beginning of the 1990s onwards, including the California's Zero Emission Vehicle (ZEV) program, the first comprehensive regulation aiming not only to reduce emissions to lower levels but also enforcing investments in zero emission vehicles.

The literature holds that, in an aggregated level, the increase in automotive eco-innovation has been conducted mostly in response to potential or effective stricter national and regional regulations and other policy instruments (Bergek & Berggren, 2014). In fact, the launch of the ZEV regulation is regularly pointed as the main determinant of the increase on R&D investments in alternative technologies (e.g. Frenken et al., 2004; Penna & Geels, 2014; Sierzchula et al., 2012). While even regional regulations can influence their global strategies (Bohnsack et al., 2015), potentially leading to a convergent movement towards green technologies throughout the whole sector (Kolk & Levy, 2004), the existence of competing green technologies at different development stages and with distinct degrees of differentiation from the dominant design implies that such convergence might be restricted to some of them (Hojnik & Ruzzier, 2015; Malerba & Orsenigo, 1996).

As previously discussed, the dynamics of such mechanism of convergence among firms in a sector is deeply rooted in the micro foundations of the evolutionary perspective on innovation (Nelson, 1991). The perceptions of the firms on the technological risks and opportunities related with different but competing technologies will likely be reflected in the allocation of resources to the development of each of these technologies, for example in their patent portfolios. At the sectoral level, if firms share perceptions about such technologies, the degree of convergence in their resource allocation over time would indicate the presence and strength of sectoral patterns of eco-innovation (Patel & Pavitt, 1997).

Faria & Andersen (2015) offers some evidence of this convergence by observing a substantial reduction of the sectors' patenting activity concentration for green Internal Combustion Engines (ICE), Hybrid/Electric Engines, and Complex patents[4]. For the group of patents related with Fuel cells, however, the reduction of concentration happened later and was significantly less intense than for the other groups, an indication that the investment in such technology is still concentrated in the hands of few firms. The present paper aims to expand these findings by analyzing the eco-innovation dynamics of this sector on a firm-level, combining with other sources of data, in order to answer the following questions:

- How incumbent automakers have been reacting strategically when faced with a complex and highly uncertain scenario, and to which degree and at what rate have their strategies been greening?
- How is their eco-innovation behavior mainly affected by external (i.e. geographic, sectoral) vis-à-vis firm-specific patterns? What is the degree of heterogeneity in the development of eco-innovation strategies (Brunnermeier & Cohen, 2003; Utterback, 1971)?
- Why and how firms have been positioning themselves about the leadership in Fuel cell technologies? Which elements can explain their decision to invest or not in such technologies?

3. Methodology

While the market diffusion of the more radical green technologies is still incipient, it is possible to observe the characteristics of the greening process by using indicators that reflect the direction of technological change. Patent-based life cycles start earlier than sales-based life cycles but they are both interconnected, i.e.

[4] This groups is formed by patents that represent the combination between two or more groups and denote a cross fertilization between the different green technologies.

the product that will be sold in the future is the result of cumulative innovative processes performed in the past (Pilkington, 2004).

The rate of growth in patenting in a certain technologic field can be used as proxy of its importance and maturity degree (Blind et al. 2009; Nesta & Patel, 2005), and patent applications are considered a robust indicator of firms' technological competences as it signs that the firm has sufficient competences to produce knowledge pieces in the technological frontier for a given technological field (Breschi et al., 2003; Chang, 2012). Despite its main limitations as an innovation indicator (Pakes, 1986; Pavitt, 1985), patent grants can be used as a proxy for the level of eco-innovation activity and also to analyze changes in the technological trajectory in a given sector, particular in medium-high tech industries such as the automotive industry (Oltra et al., 2010).

3.1 Data description

To conduct our analysis, patent data was collected from the Derwent World Patent Index (Thomson Reuters), from 1965 to 2012. The sample of firms was chosen based on two requirements: first, that the automaker must be listed on the OICA's (International Organization of Motor Vehicle Manufacturers) World Motor Vehicle Production ranking 2012; and second, that the number of patents filled on the selected patent offices must be of at least 500 up to 2012. Based on these criteria, we selected 18 car manufacturers (See Table 1).

The chosen manufacturers are all big multinational companies representing 90% of global sales of passenger vehicles (2012) and with considerable R&D expenditures, even though the degree of patenting activity varies considerably, as demonstrated in Table 1. These major incumbents have a crucial role in defining the technological strategies of the sector, influencing all the other important actors in their decision processes (Malerba & Orsenigo, 1997; Pavitt, 1984). The sample does not include relevant actors (e.g. automakers from developing countries, suppliers, universities, research centers, new entrants), as we avoid adding too much complexity to the analysis. Moreover, it is expected that the major innovations from these actors will likely be reflected (albeit indirectly) in the automakers' technological strategies.

To avoid low-quality patents, we selected only granted patents filled in the European Patent Office (EPO), US Patent Office (USPTO), and World Intellectual Property Organization (WIPO) (de la Potterie, 2011; Johnstone et al., 2010; Popp, 2005) and grouped them by technology. In opposition with most studies using patents to analyze eco-innovative activities in the automotive sector (e.g. Rizzi et al., 2014; Sierzchula et al., 2012; Wesseling et al., 2014), we identified the IPC [International Patent Classification]codes related with each technology (Pilkington & Dyerson, 2006) using the recently developed IPC Green Inventory and the OECD's list of Environmentally-sound technologies (EST), therefore including patents that may be ignored by keyword-based searches (Veefkind et al., 2012). The complete list of codes is listed on the Appendix A.

We identified patents related with the leading green powertrain technologies: Internal Combustion Engines' (ICE) green technologies – the incremental innovations associated with the dominant design, as well as Hybrid/Electric propulsion systems, and Fuel cells, more radical technologies both in terms of complexity and potential of environmental impact reductions Since every patent can be attributed with more than one IPC code, some patents may be attributed to two or more of the selected groups of technologies (e.g. fuel cells and electric/hybrid, fuel cells and ICE, ICE and hybrid/electric and so on). Here, we call these special group *Complex patents*. Because they present codes related with more than one group of technologies, they represent the "cross-fertilization" between these groups.

[TABLE 1 HERE]

To capture the level of specialization of the firms in a given green technology, a Relative Technologic Specialization Index (RTSI) is calculated, derived from Relative Specialization index (Balassa, 1963; Brusoni & Geuna, 2005; Chang, 2012; Debackere & Luwel, 2005; Nesta & Patel, 2005; Soete, 1987) which is commonly used as an indicator of relative specialization in international trade , in order to measure the evolution of individual firms' relative specialization on the specified technological areas. The formula for the RTSI for a given year is

$$\mathrm{RTSI_{ij}} = \frac{\left(\mathrm{P_{ij}}/\sum_{\mathrm{i}} \mathrm{P_{ij}}\right)}{\left(\sum_{\mathrm{j}} \mathrm{P_{ij}}/\sum_{\mathrm{i}}\sum_{\mathrm{j}} \mathrm{P_{ij}}\right)}$$

where $\mathrm{P_{ij}}$ represents the number of patents from technology *i* on the patent portfolio of firm *j*. The RTSI compares the share of a given technology *i* within the portfolio of firm *j* with the share of the same technology for the whole sample of firms as a measure of relative technologic specialization.

In order to attenuate the effects of the largest patentees in our sample, we adopted an average of all firms' share:

$$RTSI_{ij} = \frac{\left(P_{ij}/\sum_i P_{ij}\right)}{\frac{1}{n}\sum_j \left(P_{ij}/\sum_i P_{ij}\right)}$$

Using the patent data and the RTSI, the analysis is conducted through two steps, summarized in the next subsections.

3.2 Descriptive analysis of the firm-level dynamics of eco-innovation

In the first part of the analysis, the RTSI values for each firm and technology are used to conduct a descriptive analysis of the automakers' strategies on a firm-level through a series of graphs in which we plot the average and standard deviation of the RTSI values in four different time phases divided according to major milestones in the greening of the automotive sector:

- Phase AB, from 1965 to 1986, covers the era of implementation of the earliest environmental regulations and experimentation with green technologies in the sector;
- Phase BC, from 1987 to 1996, covers the rise of the sustainable development discussion, the implementation of stricter regulations such as the Carb ZEV, and the formation of partnerships between automakers and other stakeholders such as the U.S.-based Advanced Battery Consortium (1991) and the Partnership for a New Generation of Vehicles (PNGV) (1993), the Automotive Research and Technological Development Master Plan (1994) and the "Car of Tomorrow" task force (1995) in Europe.;
- Phase CD, from 1997 to 2007, covers the first mass market innovations, i.e. the hybrid Toyota Prius, and the tightening of the emissions regulations targeted to ICE vehicles worldwide, as well as the rise of hydrogen-based investments and incentives;
- Phase DE, from 2008 to 2012, covers the effects of the crisis and the introduction of new electric vehicles such as Nissan Leaf, Tesla Roadster and Model S.

The RTSI values are normalized in order to simplify and compare symmetrically the results (Nesta & Patel, 2005):

$$RTSIn_{ij} = \frac{(RTSI_{ij} - 1)}{(RTSI_{ij} + 1)}$$

The index is able to reveal how firms develop and change their technology portfolios – and consequently their strategies – over time. Accordingly, if [-1 < *RTSIn* < 0], the firm *j* has a smaller share of patents on technology *i* than the sector average and the closer to -1, the less specialized is the firm on such technology. In contrast, if [0 < *RTSIn* < 1], a firm is more specialized on the technology than the sector average. A *RTSIn* = 0 indicates that the firm *j* follows the average patenting activity of the sector for technology *j*.

When analyzed over time, the index is also able to capture changes in opportunities and persistence in firms' strategies. If, for instance, the index is moving away from -1 and stabilizes around 0, it might indicate that the firm is in a process of *technological catching up*. If the index is consistently over 0 (and especially over 0.3), it indicates that such firm has a persistent relative specialization on the technology analyzed (Nesta & Patel, 2005).

The data is presented in a series of graphs, each one divided in four quadrants according to the average portfolio of the firms in the sample (*RTSIn = 0*) in the y-axis and average standard deviation in the x-axis, as demonstrated in the Figure 1. Accordingly, firms in the top left quadrant maintain high and stable specialization ("leaders"), while firms in the bottom left have consistently very little or no specialization over the period ("laggards"). Finally, the top and bottom right quadrants represent firms that have unstable high and low specialization profiles, respectively, and could be considered "experimenters" (although that might not be necessarily true for firms in the top right quadrant).

The two dashed lines in the y-axis represent the superior and inferior limits of the average portfolio (Nesta & Patel, 2005), and the firms inside the grey area present an stable/unstable RTSI that is similar to the average portfolio of firms in the sample. The *sectoral convergence* is observed if most firms are moving towards the stable average (left grey area) over time.

[FIGURE 1 HERE]

3.3 Econometric analysis on the determinants of technological strategies on Fuel cells

Following the discussion in Section 2, we propose that firms' decision to become specialized (or not) in fuel cell technologies, or to develop a technological strategy that contemplates such technologies, is a function of its internal and external characteristics. We aim to isolate the effect of some of the main characteristics that may affect such decisions, namely: a) the effect of internal assets that might affect firms' propensity to develop fuel cell technologies; b) the country-specific determinants; and c) the effects of external shocks.

A panel is constructed using the patent data and RTSI previously calculated for the years 2003 to 2012 (10 years) for 16 automakers[5], combined with additional firm-level data (R&D expenditures, sales, profit margins) collected from the Orbis database (Bureau van Dijk), in order to test which characteristics of firms are positively or negatively related with the relative technological specialization in the Fuel cells patenting.

We estimate a Random effects linear model using the following reduced form equation, adapted from Brunnermeier & Cohen (2003):

[5] Isuzu and Porsche were excluded due to lack of firm-level data for the period analyzed.

$$\left(\mathrm{RTSI\_FC}_{i,t}\right) = \alpha_i + \gamma_t + \beta_1\left(\mathrm{PROFMG}_{i,t}\right) + \beta_2\left(\mathrm{RNDINT}_{i,t}\right) + \beta_3\left(\mathrm{LOGPAT}_{i,t}\right) + \beta_4\left(\mathrm{LOGSALE}_{i,t}\right) + \beta_5\left(\mathrm{REG\_NA}_i\right) + \beta_6\left(\mathrm{REG\_ASIA}_i\right) + \beta_7\left(\mathrm{FINCRISIS}_{i,t}\right) + \varepsilon_{it}$$

where *RTSI_FC* stands for the Revealed Technological Specialization Index for Fuel cells (dependent variable), representing firms' technological specialization. As independent variables, we use profit margins (*PROFMG*), R&D intensity[6] (*RNDINT*), total patenting (*LOGPAT*), and sales (*LOGSALE*) to represent the effects of firms' financial health, internal resources and size, as discussed in Section 2; two binary variables for geographical-specific effects (*REG_NA* for North American and *REG_ASIA* for Asian firms, Europe is omitted in the model) are included to capture the effects of regional elements; and one binary variable representing the 2008 crisis to capture the effect of such external shock (*FINCRISIS* = 1 if year ≥ 2009, 0 otherwise). α_i, γ_t and ε_{it} captures, respectively, unobservable firm heterogeneity, time effects, and other unobservable effects (residual error).

Additionally, we use the firms' RTSI relative to green ICE (*RTSI_ICE*), electric/hybrid engines (*RTSI_EV*) and complex patents (*RTSI_COMP*), and their average number of inventors (*AVGINV*) and assignees (*AVGASSIG*) per patent as control variables. The inclusion of the first three is due to possible complementarities in the development of such alternative green technologies as they share common elements, while the last two variables capture the effect of technological complexity (Maraut et al., 2008). Table 2 summarizes the basis statistics.

[TABLE 2 HERE]

4. Data analysis and discussion

4.1. Descriptive analysis of the firm-level dynamics of eco-innovation

The Figure 2 shows the average share of green technologies in automakers' patent portfolios, or the point where the RTSI = 0 for each year in the sample (Section 3). Any agglomeration observed in the firms' individual RTSIs would mean that firms are converging *to these trajectories*.

[FIGURE 2 HERE]

While the share of firms' patent portfolios devoted to ICE technologies increased considerably since the first years of the sample, it has been declining slightly since the mid-2000s while the share related with alternative technologies has been increasing considerably. In line with the core evolutionary thinking (Nelson & Winter, 1982), it demonstrates the cumulative, path dependent nature of green technological development in a sectoral level, marked by smooth increases in the patent shares.

Many scholars agree that the development of alternative technologies in the automotive sector was marked by successive movements of excitement and weakening over the last two decades, mainly caused by shifts in policies (e.g. CARB regulation in U.S., European emission standards) and changes in firms' expectations (Bakker, 2010; Dijk & Yarime, 2010; Sierzchula et al., 2012). For instance, Bakker et al. (2012) described three periods, the first from 1990 to 1997, when automakers started to explore batteries for electric vehicles (EVs), the second from 1998 to 2005, when frustration over experiences with EVs led to a movement from electric to fuel cell technologies, and subsequently (2006-2009) a movement towards the revival of electric and hybrid technologies. Our analysis, however, relativizes the intensity of such fluctuations at the sector

[6] Following other analysis in the field, we do not impose a lag structure for R&D intensity and profit margins (Brunnermeier & Cohen, 2003; Hall et al., 1986).

level as the data reveals a cumulative pattern of knowledge creation rather than periodic fluctuations in the patenting activities for the technologies considered.

The Figure 3 shows the dynamics of automakers' technological strategies for green ICE. Each dot represents a firm's average RTSI during one of the five phases described in the subsection 3.2. Each firm has a correspondent number, listed in the Appendix B. Although it is not possible to track every firm due to the amount of data in the graphs, the objective is to recognize the patterns and dynamics, for which the figures are useful.

[FIGURE 3 HERE]

The pressures to develop green internal combustion engine technologies started already in the 1970s with the implementation of a series of policy instruments (e.g. the 1970 Clean Air Act in U.S.) aimed at reducing the emissions of vehicles through, for instance, catalytic and other motor control technologies. After a leap in the emission reduction, however, the trend was reverted as the oil prices went down in the beginning of the 1980s and the number of new environmental policies decreased (Kuik, 2006; Penna & Geels, 2014). The patenting behavior reflected these trends (Figure 2 and 3). In the first phase of green ICE can be defined as an experimentation period (the blue dots represent the position of firms in the first phase, see Figure 3), since most firms are placed in the bottom right quadrant below the dotted line, indicating that they were briefly generating knowledge in this technology group but still not demonstrating long-term commitment, which only manifests in the subsequent phases.

In the following phase, BC, we observe that most firms converge towards the average zone and move to the quadrants in the left, as the red dots show in the graph. These changes persisted for in the subsequent phases (green and orange dots) and indicate that *sectoral-wide patterns* were gradually formed for this technology. These patterns reflect widely perceived opportunities and risks that were quickly perceived by most firms and influenced their technological strategies for the next periods (See Section 2). Comparing the convergence in Figure 3 with the trend in Figure 2, we infer that the firms are converging towards a strategy of maintaining or even reducing the share of patenting activity devoted to this group of technologies.

The same convergence movement is observed for the Electric and Hybrid technologies (Figure 4), although in this case it is associated with an increase of the participation of these technologies in firms' patent shares (Figure 2). Even though a number of pioneer instruments were implemented in the first phase, including the "Electric and Hybrid Vehicle Act of 1976" which aimed to establish a demonstration program to make the country an all-electric car economy by the year 2000 (Høyer, 2008), the convergence has been more gradual than for this group than for green ICE, perhaps reflecting the risks represented by their relative distance from the dominant design. Many firms were already positioned in the average stable zone in the first and second phases, but the sector-wide convergence only emerged in the period CD (1997-2007) onwards.

[FIGURE 4 HERE]

With stricter regulations having significant effects on the technological opportunities and risks, many automakers started to invest seriously in electric and hybrid propulsion motors from the 1990s and 2000s, thus explaining the convergence. A clear example is the evolution of BMW's RTSI over this period: the automaker conducted a "catching up movement" (RTSI moving away from -1 and closer or above 0) in the early 1990s on EV/HEV and complex patents, and the same with Fuel cells' patents in the late 1990s (see Figure 5). Other automakers also had similar movements, including Daimler, Fuji, Hyundai, Mazda (for a brief period), Mitsubishi, Porsche and Volkswagen.

[FIGURE 5 HERE]

The development of Complex patents, which represent the cross-fertilization between one or more green technologies, has been subject to an even more recent process of convergence (Figure 6) that only took shape in the last period, DE, after 2008, although also here it was clearly a gradual process over all phases. Even more interesting is to compare with the results in Figure 2, which shows a significant increase in firms' share of this group of patents in the same period. Therefore, more than a simple average, the trend described in that figure reflects a pattern of strategic change among most firms in our sample.

[FIGURE 6 HERE]

Finally, the evolution of fuel cells shows the weakest convergence of the four groups, corroborating the findings of Faria & Andersen (2015), which indicated that this technology has maintained relatively more concentrated than the others (Figure 7), in line with other findings in the literature (Penna & Geels, 2014). In fact, few firms had any fuel cell specialization in the first two phases, while during the phase CD (1997-2007) most firms established a position in the left quadrants but in *divergent* directions, creating two groups: one of highly specialized firms in the top and another of low specialized firms in the bottom – only Ford situated in the "average zone" during the last phase.

[FIGURE 7 HERE]

To put the dynamics of firms' technological strategy in perspective, we ran a Ward's cluster analysis over the whole period (1965-2012) to group firms according to patterns in their strategic behavior (Chang, 2012), as measured by their RTSI average and standard deviation in each of the phases[7]. The cluster analysis uses an agglomerative algorithm to group the firms according to similarities in their variance over time. It starts out with *n* clusters of size 1 and keeps agglomerating until all the observations are included into one cluster (Murtagh & Legendre, 2011; Ward Jr, 1963) as shown in Figure 8.

[FIGURE 8 HERE]

The dissimilarity measure indicates the Euclidian distance among the firms' RTSI variation, and the higher its value before two clusters "merge" (indicated by the connecting lines), the higher is the dissimilarity among them. Likewise, we found a low dissimilarity when the last groups merge for the ICE technologies (L2-squared around 5), thus the differences between the two groups are minimal. The distance is slightly higher for Electric and Hybrid technologies and for Complex patents, where firms' strategies took more time to converge, but the highest – by far – is the one for Fuel Cells, reaching a [L2-squared > 30] before the two last groups merge.

The results suggest that is possible to distinguish two major clusters for each technology, which are described in the Appendix C. The validity of the cluster analysis is examined through an one-way MANOVA, as in Chang (2012). The p-values are all significant (at 5% confidence level), confirming that there are significant differences between the two groups for each technology. The marginal tests, however, show that the differences between the two major groups have been reducing for Electric/Hybrid and Complex technologies, as the two coefficients related with the last phase (EV_DE and COMP_DE) are not significant. The differences in the RTSI among these two clusters in each technologic group are summarized on Table 3 below.

[7] Two firms, Renault and PSA, were excluded of this analysis due to lack of data in the two first phases.

[TABLE 3 HERE]

For each technology, Cluster 1 seems to represent the “laggards”, while the Cluster 2 represents the “leaders”, although, as mentioned, the distance between the groups reduces in the last phase for some groups. By combining the position of each firm in the four technologies as a new cluster analysis (Figure 9 and Appendix C), we recognize two major groups that represent the overall leaders and laggards in the relative specialization in green technologies in our sample.

[FIGURE 9 HERE]

The one-way MANOVA overall results also validate this second cluster analysis for all technologies but ICE (see Appendix D). We interpret this as a sign that the firms that are the relative “leaders” in the alternative technologies are not necessarily the leaders in the green ICE specialization. Table 4 summarizes the differences in the RTSI between the two major groups of “leaders” and “laggards”. Also in this data we observe the gradual convergence between the two groups in the last phases at the point that there is virtually no difference between the technological specialization of the leaders and the laggards. Again, the only exception is Fuel cells, for which the distance of the two groups is remarkable even in the last phase.

[TABLE 4 HERE]

We conclude, from this first analytical effort, that most firms in the sector have experienced increased convergence in their technological strategies for green ICE, Electric/Hybrid, and “Complex” technologies. For the last two technologic groups, this meant an increase in the share of these technologies on firms’ patent portfolios (Figure 2), while for the former we observe the opposite. The analysis indicates that, at least for the patenting activity, we are observing the gradual formation of robust sectoral patterns of eco-innovation in this sector. As discussed, this might be a strong indicator that technological opportunities are being collectively perceived by most firms in the sample, overcoming the eventual risks that are associated with changes in technological strategies (see Section 2).

However, this conclusion is not valid for Fuel cells, as both the evolution of the RTSI and the Cluster analysis point to the existence of two very distinct groups among the sample. As discussed in Section 2, besides sector-specific elements, other determinants – such as geographic or firm-level characteristics – might be contributing to the formation of divergent technological strategies for this technology. In the next subsection, we further investigate the correlation of some of these elements on the fuel cell specialization.

3.2 Econometric analysis on the determinants of technological strategies on fuel cells

This subsection present the results of the econometric analysis, in which we inquiry into firm-specific characteristics that might have had an influence on their decision to specialize in fuel cell technologies, as measured by their relative specialization indexes. Specifically, we aim to test the influence of firms’ financial health (profit margins), innovation efforts (R&D intensity and size of patent portfolios), size (sales), headquarters’ location, and the consequences of the financial crisis.

Although firm size and R&D expenditures are regarded as important drivers of innovation activities in the evolutionary literature (Cohen et al., 1987; Patel & Pavitt, 1997; Schumpeter, 1942; Shefer & Frenkel, 2005), empirical analyzes have generated inconclusive evidence of their role as eco-innovation drivers (Table 5). Other potential drivers – firms’ financial health, headquarters’ location, and exogenous shocks, have been little investigated (del Río, Peñasco, & Romero-Jordán, 2016), but the few analyzes conducted also show inconclusive evidence.

[TABLE 5 HERE]

In our analysis, we investigate how and if these factors affecting firms' technological (relative) leadership – rather than firms' investments in eco-innovation – in one specific green technology, namely fuel cells. The objective is to find correlations between firms' characteristics and the specialization in fuel cells that might explain the results generated in the previous analysis, were we found two divergent patterns of specialization over the last two phases. The results of the econometric analysis are summarized in the Table 6 below.

[TABLE 6 HERE]

The coefficients in all regressions indicate a positive and significant correlation between firms' profit margins and the relative specialization in fuel cells technologies. The size of the patent portfolio is also significant and positively correlated with the dependent variable. Almost all regressions also point out that the 2008 crisis had a significant negative effect over the technological strategies in fuel cells. Thus the general economic situation and firms' financial health are indeed important determinants of the divergence between the firms in the sector regarding this technology.

However, the positive effect of profitability over green technology development might not be valid for all alternative technologies: Wesseling et al. (2015) found a negative association between the current profitability and firms' decision to invest in EV (electric vehicles) technologies. The variables representing firm size and R&D intensity presented no statistically significant effect on FC specialization, as many authors suggest (see Table 5). This might be explained by the intrinsic competitive, technological and productive conditions in this sector, namely its requirements of high capital intensity and intense product innovation dynamics (Zapata & Nieuwenhuis, 2010).

Finally, the dummy variables representing the geographic location are not significant, reinforcing the idea that large firms in automotive industry are in fact global and their technological strategies are becoming more independent of the specific conditions in their home countries. Among the control variables, the regressions found a positive but statistically weak correlation between the specialization in fuel cells and in two other groups of technologies, namely Hybrid/Electric and Complex patents. This correlation is grounded in the fact that these technologies share many components, and the development of Hybrid and Electric cars may have provided an important push to the development of fuel cell technologies (van den Hoed, 2007).

5. Conclusions

This article sheds light on some important but underestimated elements of the green industrial dynamics: the evolution of firms' eco-innovation strategies, the gradual formation of sectoral-specific patterns in firms' strategies, and the role of firm-specific characteristics in explaining divergent strategic behaviors. While realizing that patents can only inform us partly on eco-innovation activities, the analysis so far has proven valid for investigating important green competitive restructuring of the automotive industry.

Our findings indicate that the evolution of eco-innovation activity in the sector - measured through the patenting activity of the main automakers - for the last 40 years was marked by a gradual convergence among firms' share of green patents in three of the technologic groups analyzed – green ICE (internal combustion engines), Electric/Hybrid and Complex patents – with no significant effect of firms' home country and other structural characteristics. The results corroborates some hypothesis in the literature and challenges others: first, the fact that most automakers are developing diverse green technologies confirms that the greening of the sector is causing the technological variety in the sector to increase over time (Frenken et al., 2004; Oltra & Saint-Jean, 2009b).

Second and most important, the convergence among automakers' green technological strategies, despite significant regional differences in environmental policies and organizational profiles (Rugman & Collinson, 2004), suggest a process of co-evolution of firms' strategies and indicates the existence of s*ectoral-specific patterns of eco-innovation* in this sector (Malerba, 2002a; Oltra & Saint-Jean, 2009a). Moreover, the results show the cumulative nature of green technological development in a sectoral level and relativizes the effects of hype cycles.

The findings points that the convergence is *technology-specific*: we observed that the group of Fuel cells presented two divergent technological trajectories, generating contrasting groups. Previous studies highlighted the role of institutional stimuli (mainly the ZEV regulation and the role of leaders such as Daimler and General Motors) technological advantages (e.g. better learning curves when compared with the other alternative technologies), and firms' expectations affecting the decision to develop Fuel cell technologies in the automotive industry (Budde et al., 2012; van den Hoed, 2007). We expanded these findings by examining other firm-specific characteristics that may affect this decision and lead to divergent trajectories.

The econometric analysis indicates that the general economic situation and firms' financial conditions are indeed important determinants of the divergence between the firms in the sector regarding fuel cells. The literature points that developing riskier technologies requires healthy economic track records from innovating firms (Cainelli et al., 2006; Cyert & March, 1963; Forsman, 2013). Likewise, the development of fuel cells is considered complex and riskier when compared with the other alternative technologies due to high uncertainty on the costs of hydrogen production, distribution and storage (Debe, 2012; Maxton & Wormald, 2004; Pilkington, 2004).

Because fuel cells technologies offer more risks for being perceived as more uncertain and complex, only automakers with healthier economic conditions would have enough incentives to develop it when balancing the opportunities and risks associated with this decision. As a policy advice, these findings recommend that, besides providing institutional stimuli such as regulations demand-pull, policymakers have to create conditions to maintain firms' incomes during the transition process associated with the greening of the economy, especially during severe economic crisis (Andersen, 2008). It is possible that the negative effect of the financial and economic crisis over the greening of the economy can be stronger than previous though for radical technologies (Archibugi et al., 2013), perhaps even more than the institutional inertia. Finally, we emphasize that the relationship between the green transition and financial health may be increasingly subject to feedback mechanisms as environmental performance becomes important to stakeholders (Rennings & Rammer, 2011)[8].

[8] Two months after admitting that it had deliberately equipped 11 million of its diesel vehicles with a "defeat device" to "cheat" at U.S. emissions testing, Volkswagen saw its reputation for environmental friendliness melt, its rating at

We acknowledge that these findings are subject to methodological and data limitations. The use of patents to measure innovative activity is far from perfect (Griliches, 1990; Pakes, 1986), and many innovations simply cannot be patented and many are not patented because it may be easier – and safer – to restrict competitors' access to technical information about new industrial processes instead of disclosing the information required for patenting them. Moreover, our sample does not include first-tier suppliers, big automakers from emerging countries – especially China and India, and new entrants such as Tesla Motors. We are also not able to capture recent events – including the Volkswagen scandal mentioned earlier and the overvaluation of Tesla Motors' stocks, on firms' technological strategies.

Our paper contributes to the literature as a multi-level analysis of the eco-innovation dynamics, tracking micro-level, firm-specific behavior in terms of technological strategies to explain the formation of sectoral patterns of change. It increases our understanding of the dynamics of sectoral eco-innovation patterns, their formation and strength, depending on technology- and firm-specific elements. Additionally, the paper offers methodological insights for the study of dynamics of eco-innovation at the firm and sector levels by using the patent analysis together with the indexes selected, which can be expanded to other sectors.

Several inquiries remain in order to take this analysis towards the aggregate level of inter sectoral eco-innovation patterns and wider understandings of green economic change. Investigations such as the induced effect of the automotive industry on other industries and vice versa, and on identifying the degree to which the automotive sector has been an early or late entrant into the green economy, the degree of green market maturity relative to other industries and indeed to which degree the automotive industry may be characterized as a carrier industry for the greening of the economy. These issues require the expansion of the analysis conducted in this paper to other sectors, for what our methodology could serve as reference.

Moody's drop one notch, the company's market capitalization dropped 40% and it was charged in 6.7 billion Euros, not including future penalties or compensations (Blackwelder et al., 2016).

Appendix A. List of IPC (International Patent Codes) for each technologic group

ICE Green patents		Electric/Hybrid patents		Fuel Cells
F01N-011/00	B01D-041/*	B60K-001/*	B60K-006/*	H01M-012/*
F01N-009/00	B01D-046/*	B60K-016/00	B60L-007/16	H01M-002/*
F02B-047/06	B01D-053/92	B60L-011/*	B60W-020/00	H01M-004/86
F02D-041/*	B01D-053/94	B60L-015/*	F16H-003/*	H01M-004/88
F02D-043/*	B01D-053/96	B60L-007/1*	F16H-048/00	H01M-004/9*
F02D-045/00	B01J-023/38	B60L-007/20	F16H-048/05	H01M-008/*
F02M-023/*	B01J-023/40	B60L-008/00	F16H-048/06	B60L-011/18
F02M-025/00	B01J-023/42	B60R-016/033	F16H-048/08	
F02M-025/02*	B01J-023/44	B60R-016/04	F16H-048/10	
F02M-025/03*	B01J-023/46	B60S-005/06	F16H-048/11	
F02M-025/06	F01M-013/02	B60W-010/08	F16H-048/12	
F02M-025/08	F01M-013/04	B60W-010/26	F16H-048/14	
F02M-025/10	F01N-011/00	B60W-010/28	F16H-048/16	
F02M-025/12	F01N-003/01	H02J-015/00	F16H-048/18	
F02M-025/14	F01N-003/02*	H02J-003/28	F16H-048/19	
F02M-027/*	F01N-003/03*	H02J-003/30	F16H-048/20	
F02M-003/02	F01N-003/04	H02J-003/32	F16H-048/22	
F02M-003/04*	F01N-003/05	H02J-007/00	F16H-048/24	
F02M-003/05*	F01N-003/06	H01M-010/44	F16H-048/26	
F02M-003/06	F01N-003/08	H01M-010/46	F16H-048/27	
F02M-003/07	F01N-003/10	H01G-011/00	F16H-048/28*	
F02M-003/08	F01N-003/18	H02J-007/00	F16H-048/29*	
F02M-003/09	F01N-003/20	H01M-10/0525	F16H-048/30	
F02M-003/10	F01N-003/22	H01M-10/50		
F02M-003/12	F01N-003/24	H01M-010/04		
F02M-003/14	F01N-003/26			
F02M-031/02	F01N-003/28			
F02M-031/04	F01N-003/30			
F02M-031/06	F01N-003/32			
F02M-031/07	F01N-003/34			
F02M-031/08*	F01N-005/*			
F02M-031/093	F02B-047/08			
F02M-031/10	F02B-047/10			
F02M-031/12*	F02D-021/06			
F02M-031/13*	F02D-021/08			
F02M-031/14	F02D-021/10			
F02M-031/16	F02M-025/07			
F02M-031/18	G01M-015/10			
F02M-039/*	F02M-053/*			
F02M-041/*	F02M-055/*			
F02M-043/*	F02M-057/*			
F02M-045/*	F02M-059/*			
F02M-047/*	F02M-061/*			
F02M-049/*	F02M-063/*			
F02M-051/*	F02M-065/*			
F02M-071/*	F02M-067/*			
F02P-005/*	F02M-069/*			

Appendix B. List of automakers in the sample

Automakers			
Number	*Name*	*Number*	*Name*
1	BMW	10	Mazda
2	Daimler	11	Mitsubishi
3	Fiat	12	Nissan
4	Ford	13	Porsche
5	Fuji	14	PSA
6	GM	15	Renault
7	Honda	16	Suzuki
8	Hyundai	17	Toyota
9	Isuzu	18	VW

Appendix C. Groups of automakers according to the cluster analysis

	Technologic group				
Automaker	ICE	Electric/Hybrid	Fuel Cells	Complex	Overall
BMW	1	1	1	1	1
Daimler	1	2	2	2	2
Fiat	1	1	1	1	1
Ford	1	2	2	2	2
Fuji	1	1	1	1	1
GM	1	2	2	2	2
Honda	1	2	2	2	2
Hyundai	1	1	1	1	1
Isuzu	2	1	1	1	1
Mazda	1	1	1	1	1
Mitsubishi	2	1	1	1	1
Nissan	1	2	2	2	2
Porsche	1	1	1	1	1
Suzuki	1	1	1	1	1
Toyota	2	2	2	2	2
VW	1	1	2	2	2

Appendix D. One-way MANOVA Statistics

		Overall test			Marginal test			
		statistic*	f-value	p-value		R-squared	f-value	p-value
ICE	W	0,397	4,180	0,027	ICE_AB	0,35	7,52	0,016
	P	0,603	4,180	0,027	ICE_BC	0,18	3,09	0,101
	L	1,518	4,180	0,027	ICE_CD	0,47	12,60	0,003
	R	1,518	4,180	0,027	ICE_DE	0,30	6,11	0,027
		statistic*	f-value	p-value		R-squared	f-value	p-value
Electric/ Hybrid	W	0,167	13,720	0,000	EV_AB	0,72	35,82	0,000
	P	0,833	13,720	0,000	EV_BC	0,11	1,72	0,211
	L	4,991	13,720	0,000	EV_CD	0,24	4,39	0,055
	R	4,991	13,720	0,000	EV_DE	0,02	0,24	0,632
		statistic*	f-value	p-value		R-squared	f-value	p-value
Fuel Cell	W	0,243	8,580	0,002	FC_AB	0,48	12,89	0,003
	P	0,757	8,580	0,002	FC_BC	0,57	18,82	0,001
	L	3,119	8,580	0,002	FC_CD	0,69	30,49	0,000
	R	3,119	8,580	0,002	FC_DE	0,52	14,98	0,002
		statistic*	f-value	p-value		R-squared	f-value	p-value
Complex	W	0,319	5,860	0,009	COMP_AB	0,66	26,64	0,000
	P	0,681	5,860	0,009	COMP_BC	0,06	0,90	0,358
	L	2,132	5,860	0,009	COMP_CD	0,24	4,50	0,052
	R	2,132	5,860	0,009	COMP_DE	0,00	0,06	0,811
		statistic*	f-value	p-value		R-squared	f-value	p-value
All Groups	W	0,157	14,800	0,000	ICE	0,06	0,83	0,377
	P	0,843	14,800	0,000	EV	0,74	39,74	0,000
	L	5,381	14,800	0,000	FC	0,74	40,60	0,000
	R	5,381	14,800	0,000	COMP	0,42	10,28	0,006

*W = Wilks' lambda L = Lawley-Hotelling trace P = Pillai's trace R = Roy's largest root

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Figure 1
Dynamic comparison between firms' RTSI

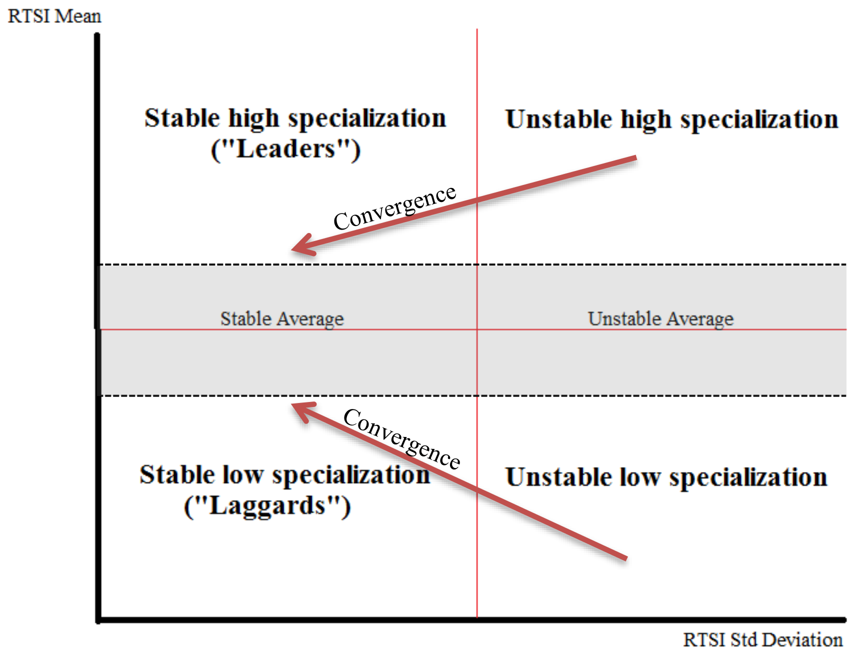

Figure 2
Average share of selected green technologies in automakers' patent portfolios

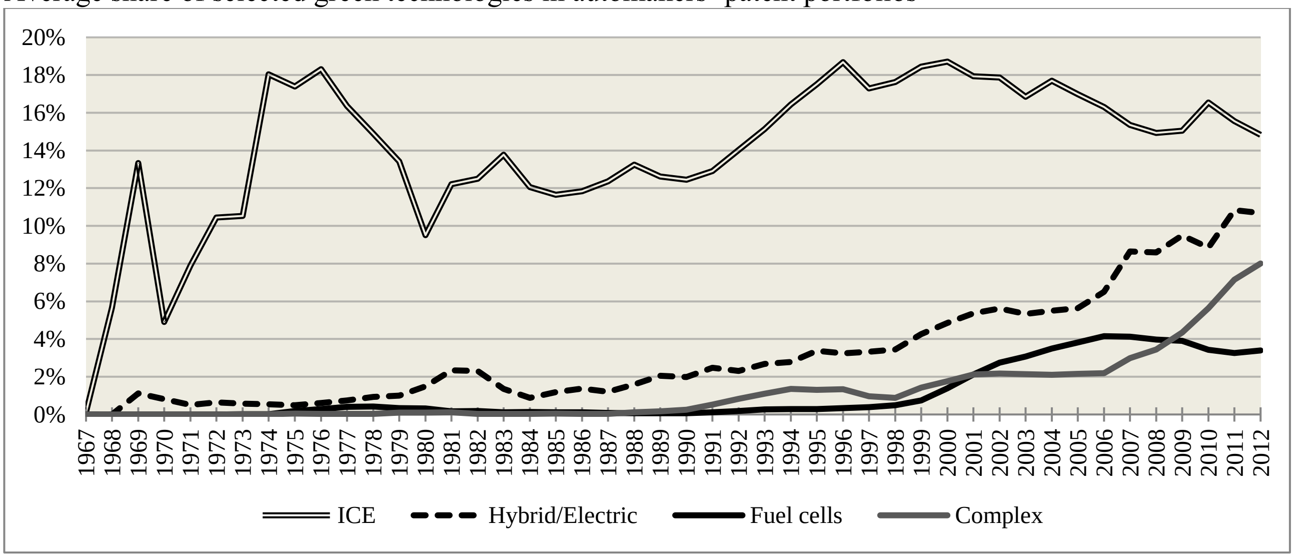

Figure 3
The evolution of relative technological specialization in green ICE

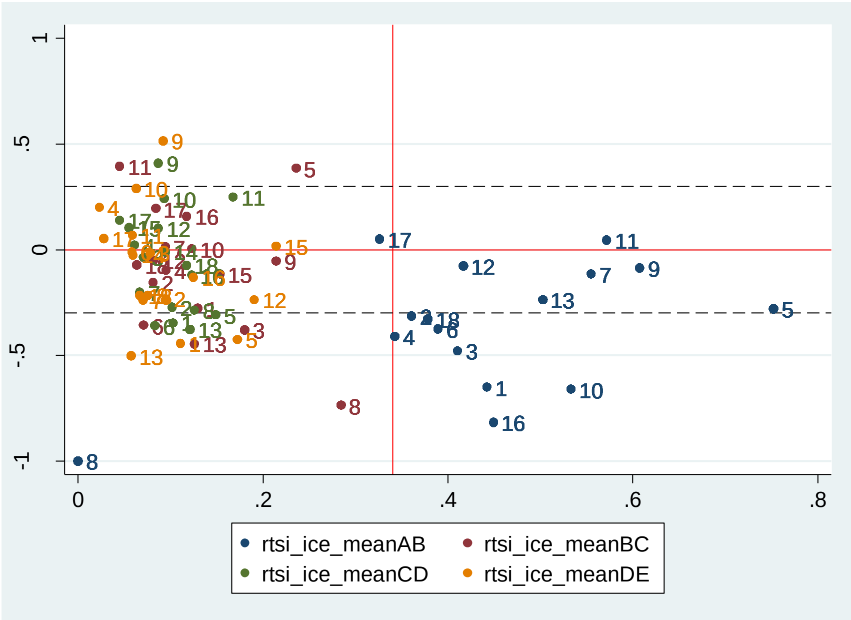

Figure 4
The evolution of relative technological specialization in Hybrid and Electric engines

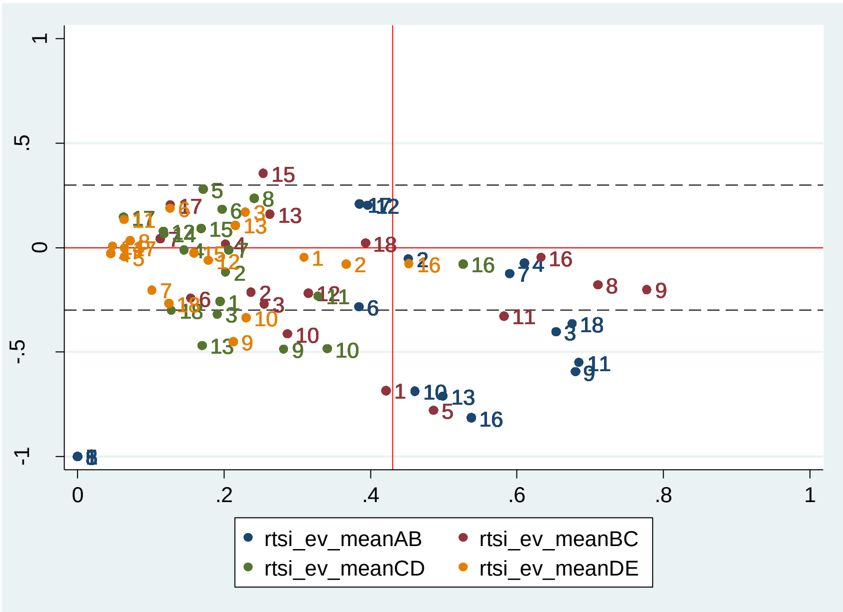

Figure 5

BMW – Relative technologic specialization index (normalized, 3 year moving average)

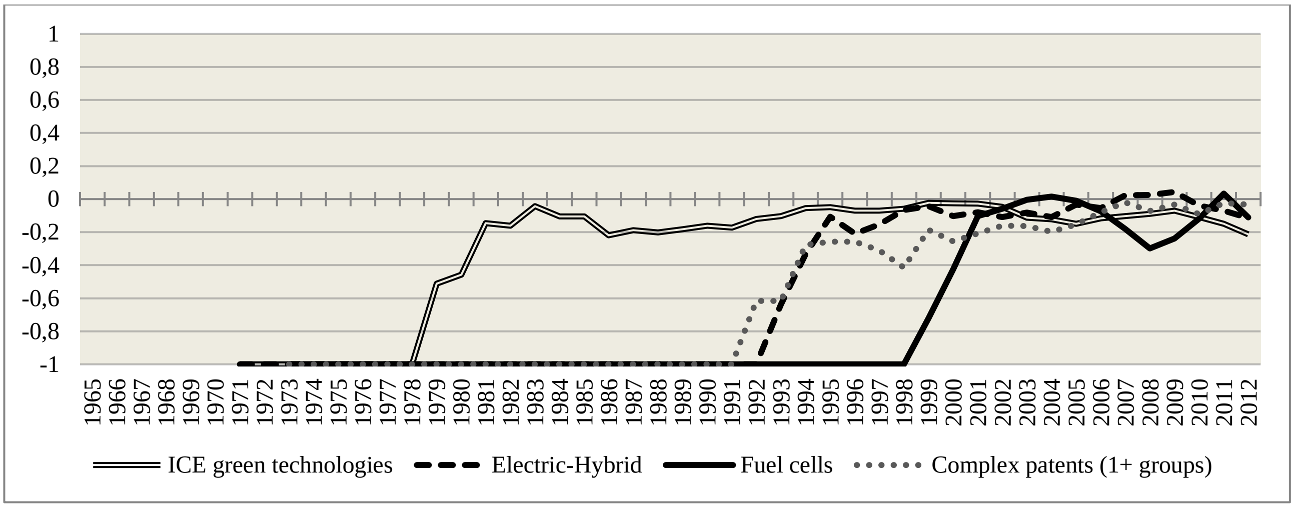

Figure 6

The evolution of relative technological specialization in Complex patents

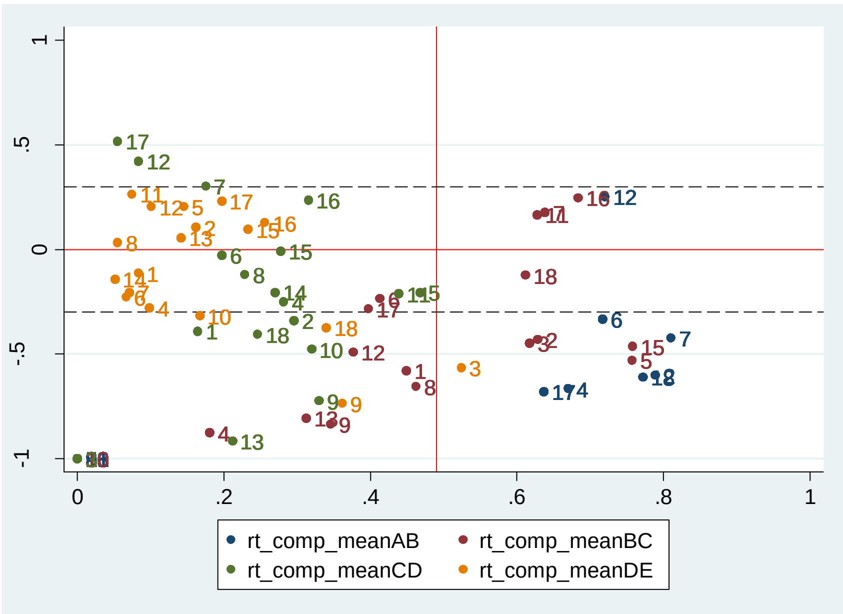

Figure 7
The evolution of relative technological specialization in Fuel cells

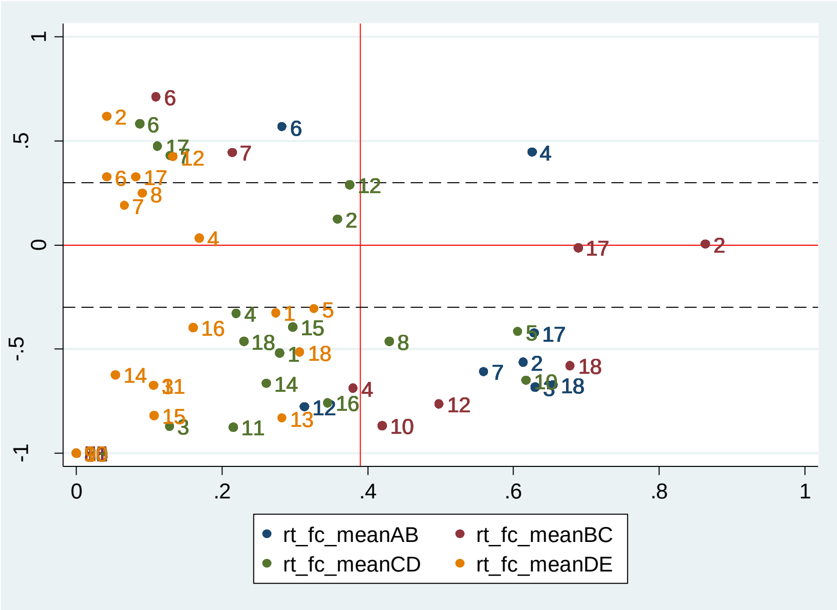

Figure 8
Patterns of technological change – Cluster Analysis

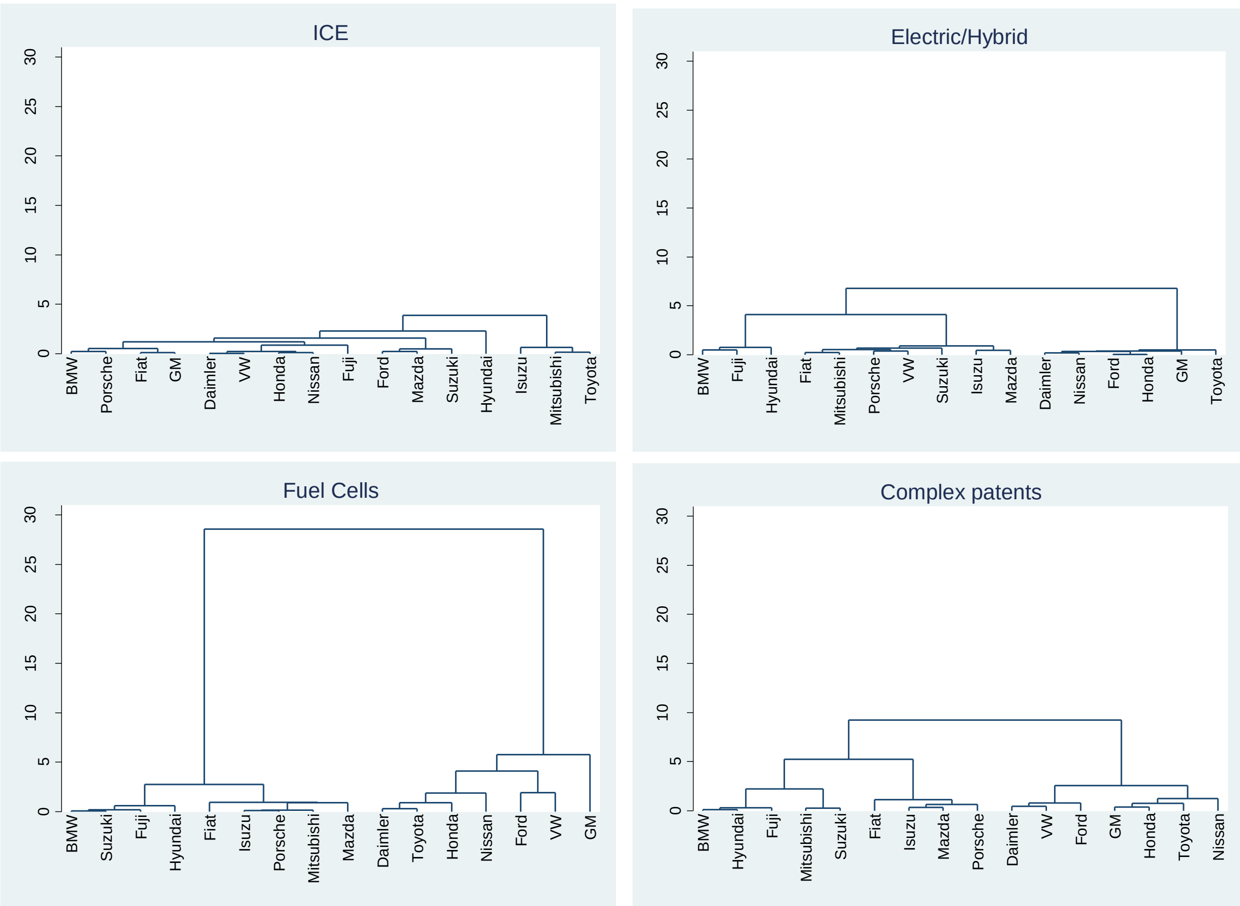

Figure 9
Relative leadership in all technology groups – Cluster analysis

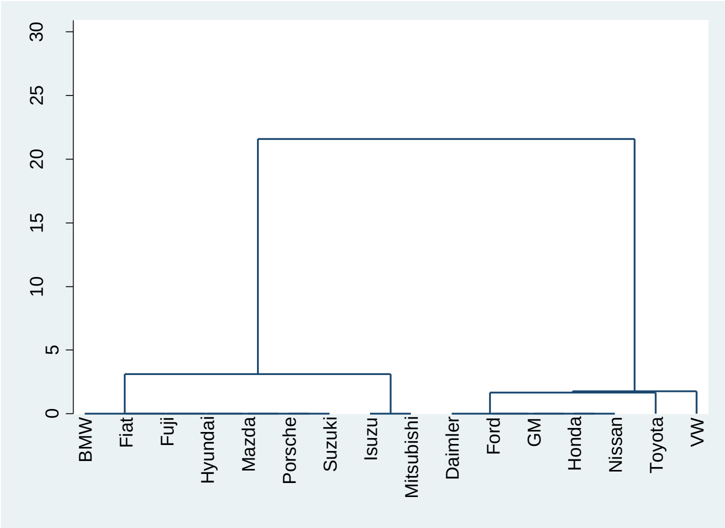

Table 1 – Patent counts per firm and technology

	Total Patents	ICE green	Hybrid/Electric	Fuel Cells	Complex Patents
BMW	5020	333	127	56	95
Daimler	7579	630	227	385	160
Fiat	2082	228	71	6	14
Ford	15823	2123	676	278	259
Fuji	1313	130	93	32	50
GM	23644	1850	1650	1313	472
Honda	21961	2181	739	1085	672
Hyundai	5728	440	418	237	287
Isuzu	1283	287	34	0	4
Mazda	3105	470	46	2	23
Mitsubishi	1680	334	66	6	66
Nissan	12831	1545	337	612	423
Porsche	2410	144	79	5	54
PSA	2977	292	164	30	88
Renault	3349	420	176	32	134
Suzuki	1351	178	66	10	84
Toyota	26769	3932	1059	1526	1605
VW	6026	539	181	54	119
Total	*144931*	*16056*	*6209*	*5669*	*4609*

Table 2 – Summary statistics

Description	*Abbreviation*	*Panel*	*Mean*	*Std. Dev.*	*Min*	*Max*	*Observations*
RTSI Fuel cells	RTSI_FC	Overall	1,121	1,180	0	4,867	N = 160
		Between		1,066	0	3,100	n = 16
		Within		0,567	-0,817	2,889	T = 10
Profit Margins (%)	PROFMG	Overall	0,032	0,055	-0,217	0,137	N = 160
		Between		0,031	-0,023	0,069	n = 16
		Within		0,046	-0,163	0,123	T = 10
R&D intensity [R&D/Sales (%)]	RNDINT	Overall	0,035	0,013	0,007	0,065	N = 160
		Between		0,012	0,010	0,055	n = 16
		Within		0,006	0,014	0,061	T = 10
Total number of patents (logN)	LOGPAT	Overall	8,309	1,033	6,433	10,195	N = 160
		Between		1,033	6,867	9,807	n = 16
		Within		0,246	7,347	9,016	T = 10
Sales (logN)	LOGSALE	Overall	11,092	0,759	9,348	12,446	N = 160
		Between		0,756	9,624	11,974	n = 16
		Within		0,191	10,470	11,608	T = 10
Headquarters' Localization - North America	REG_NA	Overall	0,125	0,332	0	1	N = 160
		Between		0,342	0	1	n = 16
		Within		0	0,125	0,125	T = 10
Headquarters' Localization - Asia	REG_AS	Overall	0,500	0,502	0	1	N = 160
		Between		0,516	0	1	n = 16
		Within		0	0,500	0,500	T = 10
Effect of Financial Crisis	FINCRISIS	Overall	0,400	0,491	0	1	N = 160
		Between		0	0,400	0,400	n = 16
		Within		0,491	0	1	T = 10
Number of Inventors (Average)	AVGINV	Overall	0,908	0,378	0,249	2,150	N = 160
		Between		0,336	0,388	1,605	n = 16
		Within		0,192	0,277	1,452	T = 10
Number of Assignees (Average)	AVGASSIG	Overall	1,047	0,486	0,084	2,297	N = 160
		Between		0,293	0,498	1,752	n = 16
		Within		0,394	0,077	2,155	T = 10
RTSI ICE	RTSI_ICE	Overall	1,069	0,779	0	4,253	N = 160
		Between		0,592	0,218	2,378	n = 16
		Within		0,526	-0,355	3,467	T = 10
RTSI Electric/ Hybrid	RTSI_EV	Overall	3,441	0,968	1,790	6,240	N = 160
		Between		0,696	2,131	5,049	n = 16
		Within		0,694	1,486	5,793	T = 10
RTSI Complex Patents	RTSI_COMP	Overall	1,354	0,269	1,020	2,540	N = 160
		Between		0,150	1,070	1,632	n = 16
		Within		0,226	0,884	2,524	T = 10

Table 3 – Differences in average RTSI among the two clusters for each technologic group

	ICE					Electric/Hybrid				
	Total	AB	BC	CD	DE	Total	AB	BC	CD	DE
Cluster 1	-0,281	-0,442	-0,157	-0,154	-0,167	-0,415	-0,713	-0,278	-0,212	-0,078
Cluster 2	0,126	0,003	0,168	0,265	0,212	-0,017	-0,021	-0,075	0,039	-0,031
Distance	*0,408*	*0,445*	*0,325*	*0,420*	*0,379*	*0,399*	*0,692*	*0,204*	*0,252*	*0,047*
	Fuel cells					Complex patents				
	Total	AB	BC	CD	DE	Total	AB	BC	CD	DE
Cluster 1	-0,853	-0,965	-1,000	-0,739	-0,551	-0,604	-1,000	-0,523	-0,407	-0,116
Cluster 2	-0,065	-0,290	-0,150	0,152	0,200	-0,235	-0,438	-0,333	0,009	-0,078
Distance	*0,789*	*0,674*	*0,850*	*0,891*	*0,752*	*0,369*	*0,562*	*0,190*	*0,416*	*0,038*

Table 4 – Differences in average RTSI among the two major clusters

		Average RTSI for each phase				
		Total	AB	BC	CD	DE
ICE	Cluster 1	-0,250	-0,463	-0,113	-0,063	-0,095
	Cluster 2	-0,147	-0,225	-0,074	-0,092	-0,098
	Distance	*|0,103|*	*|0,238|*	*|0,039|*	*|0,030|*	*|0,003|*
Electric/ Hybrid	Cluster 1	-0,434	-0,752	-0,314	-0,204	-0,057
	Cluster 2	-0,050	-0,070	-0,058	-0,007	-0,065
	Distance	*|0,384|*	*|0,682|*	*|0,255|*	*|0,196|*	*|0,008|*
Fuel Cells	Cluster 1	-0,853	-0,965	-1,000	-0,739	-0,551
	Cluster 2	-0,065	-0,290	-0,150	0,152	0,200
	Distance	*|0,789|*	*|0,674|*	*|0,850|*	*|0,891|*	*|0,752|*
Complex	Cluster 1	-0,604	-1,000	-0,523	-0,407	-0,116
	Cluster 2	-0,235	-0,438	-0,333	0,009	-0,078
	Distance	*|0,369|*	*|0,562|*	*|0,190|*	*|0,416|*	*|0,038|*

Table 5 – Empirical evidence on the effects of the independent variables over eco-innovation activity

Variable	*Statistically significant*	*Not significant/mixed evidence*
Size	Kammerer, (2009); Kesidou & Demirel, (2012); Rehfeld et al., (2007); Triguero et al., (2013); Veugelers, (2012);	Cainelli et al., (2012); Cleff & Rennings, (1999); Frondel et al., (2007); Wagner, (2007);
R&D expenditures	Belin et al., (2011); Cainelli et al., (2015); Cuerva et al., (2014); del Río et al., (2015); Ghisetti et al., (2014); Horbach, (2014); Ziegler, (2015);	De Marchi, (2012); Horbach et al., (2012); Horbach, (2008);
Geographic location	Cainelli et al., (2015);	Horbach, (2008); Ziegler, (2015);
Financial health	Cuerva et al., (2014); Wesseling et al., (2015);	del Río et al., (2015); Horbach, (2008);
Exogenous shocks	n.d.	n.d.

Source: adapted from del Río et al. (2016).

Table 6 – Panel data, Random effects linear model – Main results

Dependent variable: RTSI_FC	(1)	(2)	(3)	(4)
PROFMG	3.227***	3.271***	2.563**	2.450**
	(1.15)	(1.16)	(1.01)	(1.05)
RNDINT	-9.034	-8.342	-2.203	-0.475
	(10.60)	(10.24)	(7.68)	(6.97)
LOGPAT	0.565*	0.602*	0.618**	0.623**
	(0.33)	(0.34)	(0.29)	(0.27)
LOGSALE	-0.421	-0.411	-0.239	-0.178
	(0.53)	(0.51)	(0.42)	(0.38)
REG_NA	0.570	0.477	0.251	0.125
	(0.99)	(0.95)	(0.87)	(0.83)
REG_AS	0.047	0.023	-0.011	-0.014
	(0.81)	(0.80)	(0.74)	(0.70)
FINCRISIS	-0.194	-0.191*	-0.205+	-0.231**
	(0.14)	(0.11)	(0.13)	(0.10)
AVGINV		0.019		0.075
		(0.13)		(0.12)
AVGASSIG		0.076		-0.047
		(0.29)		(0.31)
RTSI_ICE			-0.189	-0.312
			(0.25)	(0.23)
RTSI_EV			0.184	0.252*
			(0.14)	(0.15)
RTSI_COMP			0.252+	0.250+
			(0.17)	(0.17)
Constant	1.293	0.694	-1.606	-2.499
	(4.01)	(3.90)	(3.02)	(2.69)
N	160	160	160	160

Regression coefficients are in upper rows, standard errors in brackets. Robust variance estimates were used.
Significance levels: + at $p<0.15$, * at $p<0.10$, ** at $p<0.05$, *** at $p<0.01$.